

Solar Cosmic Ray Multiply Charged Nuclei and the July 18, 1961 Solar Event

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Abstract

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Energetic helium and heavy nuclei ($Z \geq 3$) were detected in the July 18, 1961 solar particle event. This result brings to four the number of solar cosmic rays bursts in which heavy nuclei have been seen. The particles were detected in nuclear emulsions flown on a balloon launched from Fort Churchill shortly after the associated flare appeared on the sun. The average flux of medium nuclei ($6 \leq Z \leq 9$) during the early part of the solar event was 12.0 ± 1.8 particles/m²/sr sec in the energy interval from 120 to 204 MeV/nucleon, or about 40 times the normal galactic cosmic ray medium nuclei flux at that particular time in the solar cycle. The helium to medium nuclei ratio in the same energy interval was 79 ± 16 . These values are consistent with those anticipated on the basis of the relative abundance of hydrogen, helium, and medium nuclei in other events. Some large nuclei ($Z \geq 10$) were detected, but light nuclei were so rare that only an upper limit to their abundance could be set ($L/M \leq .07$). The unbiased acceleration of multiply charged nuclei in every major solar event now seems more certain, and, therefore, it seems to be worth considering this feature in any theory of solar particle acceleration.

I. INTRODUCTION

With the discovery of heavy nuclei ($Z > 2$) in solar cosmic rays, a number of interesting questions arose, which can only be answered finally after many more measurements of the charge and energy spectrum of solar cosmic rays have been made. Toward this goal, we shall report here the results of measurements made on the helium and heavy nuclei in the solar event of July 18, 1961. It will be seen that the results add weight to many of the ideas which seemed to be suggested by the samples of the solar particles measured in the three previous major solar events in which heavy nuclei were detected [Sept. 3, 1960 - Fichtel and Guss, (1961); Nov. 12, 1960 - Biswas et al. (1962) Yagoda et al. (1961) and Pomerantz and Witten, (1962); Nov. 15, 1960 Ney and Stein (1962) Biswas et al. (1963) and Biswas and Fichtel (1964)]. Therefore, after presenting the results, a brief summary will be given of the significant features of the picture which seems to be emerging.

II. EXPERIMENT PROCEDURE

The data on the solar cosmic ray heavy nuclei in the July 18, 1961 event were obtained from particle tracks in nuclear emulsions flown on a high altitude balloon launched from Fort Churchill, Canada. The balloon floated at an average altitude of only 2.07 g/cm^2 . The nuclear emulsion experiment was rotated into the vertically oriented position when the balloon reached ceiling and remained in that position between 1305 U.T. and 1918 U.T. on 18 July. The polar cap absorption as recorded by the 30 mc/sec riometer at Fort Churchill began at about 1100 U.T. on July 18, reached a maximum of

about 8 db at 1200 U.T. and remained at that level for the remainder of the day. The fact that the absorption remained at a constant level throughout the emulsion exposure period would indicate that the time average fluxes of the low energy particles are representative of the exposure period. Rapid fluctuations, even if they did occur, would not affect the ratios of the various components considered here which have the same charge to mass ratio, and, hence, behave identically in electromagnetic fields.

The emulsion stack was composed of Ilford G-2 and G-5 emulsions, and, because of the intense exposure, the G-5 emulsions were underdeveloped. In the analysis of the heavy nuclei tracks, the scan line was set 2mm from the top of the emulsion. The minimum energy for medium nuclei ($6 \leq Z \leq 9$) was, therefore, about 120 MeV/nucleon. The maximum energy of about 200 MeV/nucleon was set primarily by the rapidly decreasing flux with increasing energy, and the resulting inability to make a significant measurement above that point. The scan line for alpha particles was set 3cm from the top of the stack in order to collect alpha particles in the same energy/nucleon interval. For heavy nuclei the collection angles were $\pm 45^\circ$ with respect to the zenith in the emulsion plane and $\pm 23^\circ$ in the perpendicular plane. The angles for alpha particles were $\pm 20^\circ$ ($\pm 45^\circ$ in a small part of the sample) and $\pm 6^\circ$ respectively. The total sample consisted of 51 heavy nuclei tracks and 73 helium nuclei tracks.

The actual analysis procedure was similar to the methods used in the analysis of the particles detected in nuclear emulsions flown in

sounding rockets previously (Biswas et al., 1962). The charge determination of the heavy nuclei was made on the basis of delta ray density as a function of range, and the helium nuclei tracks were separated from the singly charged particles by measurements on their grain density and residual range. The helium nuclei analysis was very tedious due to the fact that the helium nuclei tracks had to be separated from a very large number of singly charged particle tracks of comparable grain density. There were approximately sixty singly charged particle tracks which had to be examined for every helium track found.

The extrapolation of the helium nuclei intensity to the top of the atmosphere is somewhat uncertain because of the lack of information on the energy dependence of the mean free paths. The contribution to the observed helium flux from secondary production and from fragmentation of heavy nuclei is very small in the energy range considered here, and, hence, the major concern is the absorption mean free path for helium nuclei in nuclear emulsion and in air. At high energies these are estimated to be 21.4 cm of emulsion and 51 g/cm² of air respectively; at very low energies they probably become very large. With the former values of flux of helium nuclei in the energy range 120.5 to 204 MeV/nucleon at the top of the atmosphere was found to be 1.03×10^3 particles/(m² sr sec), and with no correction 0.86×10^3 particles/(m² sr sec). A compromise value of $(0.95 \pm 0.13 \times 10^3)$ was selected for the subsequent analysis.

III. EXPERIMENTAL RESULTS

The differential flux of medium and helium nuclei at the top of the

atmosphere is given in Table I. The medium nuclei flux was determined to be 12.0 ± 1.8 particles/(m² sr sec) for the energy interval from 120 MeV/nucleon to 204 MeV/nucleon. This flux was estimated both on the basis of the numbers of particles in the interval which was common to all medium nuclei species and on the basis of the number of each type in its observed interval, since they were somewhat different, and the estimated energy spectrum. The two methods led to results which differ by considerably less than the uncertainty introduced by statistical fluctuations and other minor errors. The helium flux in the same energy interval was $(9.5 \pm 1.3) \times 10^2$ particles/(m² sr sec) giving a medium to helium nuclei ratio of 79 ± 16 . Figure 1 shows the differential helium and medium nuclei energy/nucleon spectra. From the figure, it can be seen that within the limited interval of measurement the spectra are approximately the same when the medium nuclei are multiplied by 60, the average helium to medium nuclei ratio measured in previous events (Biswas and Fichtel, 1964). If the result of this work is included with the other six measurements under the assumption they are all the same, an average helium to medium ratio of 62 ± 6 is obtained.

Of the nine heavy nuclei not in the medium class, only one was an apparent light nucleus ($3 \leq Z \leq 5$). Due to the amount of material above the detector in which light nuclei could be formed and the charge determination limitation, only an upper limit can be set to the light nuclei flux. This limit is about .07 of the medium nuclei flux. The remaining eight heavy nuclei had charges of from ten to fourteen, and were in the same range interval and therefore a higher energy/nucleon interval. On the basis of the medium nuclei flux and the relative abundances in previous solar events

(Biswas and Fichtel, 1964), five nuclei with charges of from ten to fourteen would have been expected, and, hence, the number found is consistent with the same abundances as previous events.

The galactic cosmic ray flux at this time in the solar cycle is known for the case of helium nuclei from the work of Fichtel et al. (1964), and the flux of heavier nuclei can be estimated from the general knowledge of the cosmic ray composition and the energy measurements made on low energy heavy nuclei in recent years (Fichtel et al., 1965; McDonald et al., 1965; Fan et al., 1965; and Reames et al., 1965). From these sources the following values are obtained: 6.9 ± 1.1 part./m².sr.sec. for helium nuclei with energies between 120 and 204 MeV/Nucleon and $.23 \pm .05$ and $.07 \pm .02$ part./m² sr sec) as estimates for the medium and ($Z \geq 10$) nuclei respectively in the same energy interval. Thus the galactic cosmic ray correction to the solar particle flux is negligible.

IV. DISCUSSION

The detection of heavy nuclei in the July 18, 1961 event brings to four the number of solar cosmic ray events in which heavy nuclei have been detected. Further, it now seems likely that these nuclei are always present since they have been observed every time the intensity of the event was sufficiently great to expect to see them on the basis of their abundances in other events. Figure 2 shows the proton to helium nuclei ratio for those events where this ratio has been measured. The proton data used for comparison to the work reported here is that obtained by Guss and Waddington (1963) from measurements made in the same nuclear emulsion stack in which

this work was undertaken. It is seen that there is a strong variation with energy, but some similarity from event to event.

If, on the other hand, the proton to medium nuclei ratio, or the proton to helium ratio, is compared in the same rigidity intervals, large variations (as much as a factor of 50) are found from event to event even though the proton, helium, and medium nuclei rigidity spectra are similar (Freier and Webber, 1963; Biswas and Fichtel, 1964).

If the protons are left aside and only the multiply charged nuclei are examined, much more uniformity in composition seems to exist (see, for example, Biswas and Fichtel, 1965.). The measurements on the two most abundant multiply charged types, the helium and medium nuclei, show that the relative abundances of these two species are remarkably similar, as shown in table 1. This result is especially striking considering the large variation in the proton to medium nuclei ratio or the proton to helium one. In fact, within the limitations of the experimental errors, the helium to medium ratio could be exactly the same for the whole duration of every event, with the best estimate of this ratio being about 62 ± 7 .

Table 1
Helium to Medium Nuclei Ratio

Time of measurements	Energy Interval Mev/nucleon (ΔE)	$R(\text{He}, M, \Delta E)^*$	Ref***
1408 UT, Sept 3, 1960	42.5 - 95	68 ± 21	a, c
1840 UT, Nov. 12, 1960	42.5 - 95	63 ± 14	b
1603 UT, Nov. 13, 1960	42.5 - 95	72 ± 16	b
1951 UT, Nov. 16, 1960	42.5 - 95	61 ± 13	c
0600 UT, Nov. 17, 1960	42.5 - 95	38 ± 10	c
0339 UT, Nov. 18, 1960	42.5 - 95	53 ± 14	c
_____	_____	_____	_____
Average of above readings	42.5 - 95	60 ± 7	
_____	_____	_____	_____
1225-2345 UT, July 12, 1959	150- 200	$\geq 100 \pm 35$	e
1030-1230 UT, Nov. 15, 1960	175- 280	$\approx 100 \pm 100$ - 50	d
1305-1918 UT, July 18, 1961	120- 204	79 ± 16	f

* $R(i, j, k)$ is the ratio of the flux of particles of type i in the interval k to the flux of particles of type j in the same interval.

- *** (a) Fichtel and Guss (1961)
 (b) Biswas, Fichtel and Guss (1962)
 (c) Biswas, Fichtel, Guss and Waddington (1963)
 (d) Biswas (1962)
 (e) Ney and Stein (1962)
 (f) Present Work (1966)

The previous work also indicated that the details of the composition reflected that of the sun insofar as comparisons could be made. The carbon to oxygen ratio measured in this experiment is statistically consistent with the value measured previously, namely 0.6, and the scarcity of light nuclei is also in agreement with the earlier findings. The number of large nuclei ($Z \geq 10$) found was also consistent with previous measurements, as mentioned earlier.

These results, especially the remarkable constancy of the helium to medium nuclei ratio add support to the idea that the composition of the multiply charged nuclei may be the same in each event, and therefore give weight to the concept of speaking of the composition of solar cosmic ray multiply charged nuclei. Table II summarizes the composition measurements and compares them to the relative abundances of nuclei in the sun, the galaxy and galactic cosmic rays. As we have pointed out previously, the composition of solar cosmic rays is similar to that of the sun and markedly dissimilar to that of galactic cosmic rays. Since the significance of this apparent feature has been discussed in detail previously, only a few comments will be repeated here, and a more detailed discussion can be found in the review article by Biswas and Fichtel (1965).

(a) Since the sun has abundances typical of most ordinary stars in the respects under consideration here and since these abundances are apparently reflected in solar cosmic rays, it seems reasonable to conclude that the difference in the charge composition between galactic cosmic rays and ordinary stars remains as a serious objection to ordinary stars being considered as the sole primary source of galactic cosmic rays. Thus,

Table 2

Relative Abundances of Nuclei Normalized to a Base
of 1.0 for Oxygen

Element	Solar Cosmic Rays*	Sun**	Universal Abundances***	Galactic Cosmic Rays****
^2He	107 ± 14	?	150	48
^3Li	-	$< 10^{-5}$	$< 10^{-5}$	0.3
$^4\text{Be}-^5\text{B}$	< 0.02	$< 10^{-5}$	$< 10^{-5}$	0.8
^6C	0.59 ± 0.07	0.6	0.26	1.8
^7N	0.19 ± 0.04	0.1	0.20	≈ 0.8
^8O	1.0	1.0	1.0	1.0
^9F	< 0.03	0.001	$< 10^{-4}$	≈ 0.1
^{10}Ne	0.13 ± 0.02	?	0.36	0.30
^{11}Na	-	0.002	0.002	0.19
^{12}Mg	0.043 ± 0.011	0.027	0.040	0.32
^{13}Al	-	0.002	0.004	0.06
^{14}Si	0.033 ± 0.011	0.035	0.045	0.12
$^{15}\text{P}-^{21}\text{Sc}$	0.057 ± 0.017	0.032^+	0.024	0.13
$^{22}\text{Ti}-^{28}\text{Ni}$	≈ 0.02	0.006	0.033	0.28

* Biswas et al. (1962), Biswas et al. (1963), Biswas and Fichtel (1964), and this work.

** The uncertainty of the values in this column is probably of the order a factor of 0.5. See Aller (1953) or Goldberg, Muller, and Aller (1960).

*** The uncertainty of the values in this column is hard to estimate, but is probably at least a factor of 0.5 in some cases. See Suess and Urey (1956) and Cameron (1959).

**** The uncertainty of the values in this column varies from 10 to about 30 percent. See Waddington (1960).

+ A 5/2 ratio for the abundance of ^{16}S relative to ^{18}A was assumed, the relative abundance of ^{18}A being unknown.

galactic cosmic rays probably have a very special origin, perhaps in supernovae (see for example Ginzburg and Syrovatskii, 1961).

(b) The energetic nuclei coming from the sun with charges ranging from that of helium through at least about twenty do seem to reflect the composition of the solar surface. If the composition of these nuclei is accepted as representative of the sun, the relative abundances given in Table 2 may be used to estimate the helium and neon abundances of the sun, whereas it is not possible to obtain a good estimate of the abundance of these two elements spectroscopically in the photosphere. The average helium to oxygen ratio is 107 ± 14 and the average neon to oxygen ratio is 0.13 ± 0.02 (Biswas and Fichtel, 1965). The neon to oxygen ratio is similar to the universal abundances estimated by Suess and Urey (1956) and Cameron (1959), although a bit on the low side. The helium to medium ratio is typical, but, of course, the more interesting ratio would be the proton to helium one. For reasons associated with the different energy spectra and charge to mass ratio, there is no simple reliable way to determine this ratio from solar cosmic rays alone. If the helium to medium ratio of 62 ± 7 is accepted as representative of the sun (that is the average of the present work, the previous work of Fichtel and Guss (1961), Biswas et al. (1962), and Biswas et al. (1963)) and the proton to medium value from spectroscopic data, namely 650 (Aller, 1953; Goldberg, Muller, and Aller, 1960), is used, a proton to helium ratio of 10.5 ± 4.0 is obtained. The uncertainty in this number depends on the correctness of the assumption above, the uncertainty in the helium to medium ratio, and the uncertainty in the proton to medium ratio. Hence, the estimated uncertainty placed

on this ratio is large and not too well determined.

(c) Hoyle and Tayler (1964) have pointed out that the low hydrogen to helium ratio deduced in the manner described here together with the similar ratios observed in other cosmic material is incompatible by an order of magnitude with that predicted by assuming that ordinary stellar processes are predominately responsible for the relative abundances of hydrogen and helium existing in the universe. Hoyle (1965) adds that this result together with other evidence suggests a universal density which was higher in the past than in the present.

(d) Since the solar particle propagation mechanism affects particles with the same charge to mass ratio in the same way, the similarity in the energy spectra of the helium and medium nuclei and the constancy in the composition of the multiply charged nuclei are presumably properties of the particles at the end of the acceleration phase. The Fermi acceleration mechanism (Fermi, 1949; Fermi, 1954) has been treated extensively, one of the most recent articles being that of Wentzel (1965). Hayakawa, Nishimura, Obayashi, and Sato (1965) have concluded that the Fermi process predominates, for the acceleration of nuclear particles in the non-relativistic region. Previously it has been shown (Biswas, Fichtel, and Guss, 1962) that, in general, a spectrum which is both a function of velocity and rigidity can be produced in the Fermi process with a particle having a smaller charge to mass ratio having a steeper energy spectrum at high energies. This modified Fermi mechanism would lead to similar spectra for all the nuclei with the same charge to mass ratio, but different spectra for protons and helium nuclei, as observed.

V. Concluding Remarks

The apparent consistency of the charge spectrum of the multiply charged nuclei in solar cosmic rays is a striking feature both because of the great variations in so many other features of the solar particles and because of the important physical consequences.

Thus far, there has been no evidence to indicate that the relative abundances of the multiply charged nuclei in solar cosmic ray events are not the same in every event and also the same as that of the sun's photosphere. If further experiments should confirm this picture, there will apparently be a good estimate of the helium and neon abundances in the sun. Further, theories of solar particle acceleration would have to be consistent with the multiply charged solar particles composition reflecting that of the sun, and theories of the universe would have to agree with the measured hydrogen to helium ratio.

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Figure Captions

Figure 1: Average differential spectrum for helium and medium nuclei for the period 1350 - 1918 UT, July 18, 1961. ● - He Nuclei
o - Medium Nuclei x 60

Figure 2: The proton-to-helium nuclei ratio as a function of kinetic energy per nucleon at several different times. For curves A through F, the curves represent data taken from the work of Biswas, et al., (1962), Biswas, et al., (1963), and Biswas and Fichtel, (1963). Uncertainties in the ratios range from 25 to 50 percent. The data represented by G are the lower limits set by McDonald, et al., (1965). H indicates the work reported in this paper. The times at which the measurements were made are as follows: A - 1840 UT, Nov. 12, 1960; B - 1603 UT, Nov. 13, 1960; C - 1961 UT, Nov. 16, 1960; D - 0600 UT, Nov. 17, 1960; E - 0339 UT, Nov. 18, 1960; F - 1408 UT, Sept. 3, 1960; G - March 16, 1964 and Feb. 5, 1965. H - 1305 to 1918 UT, July 18, 1961.

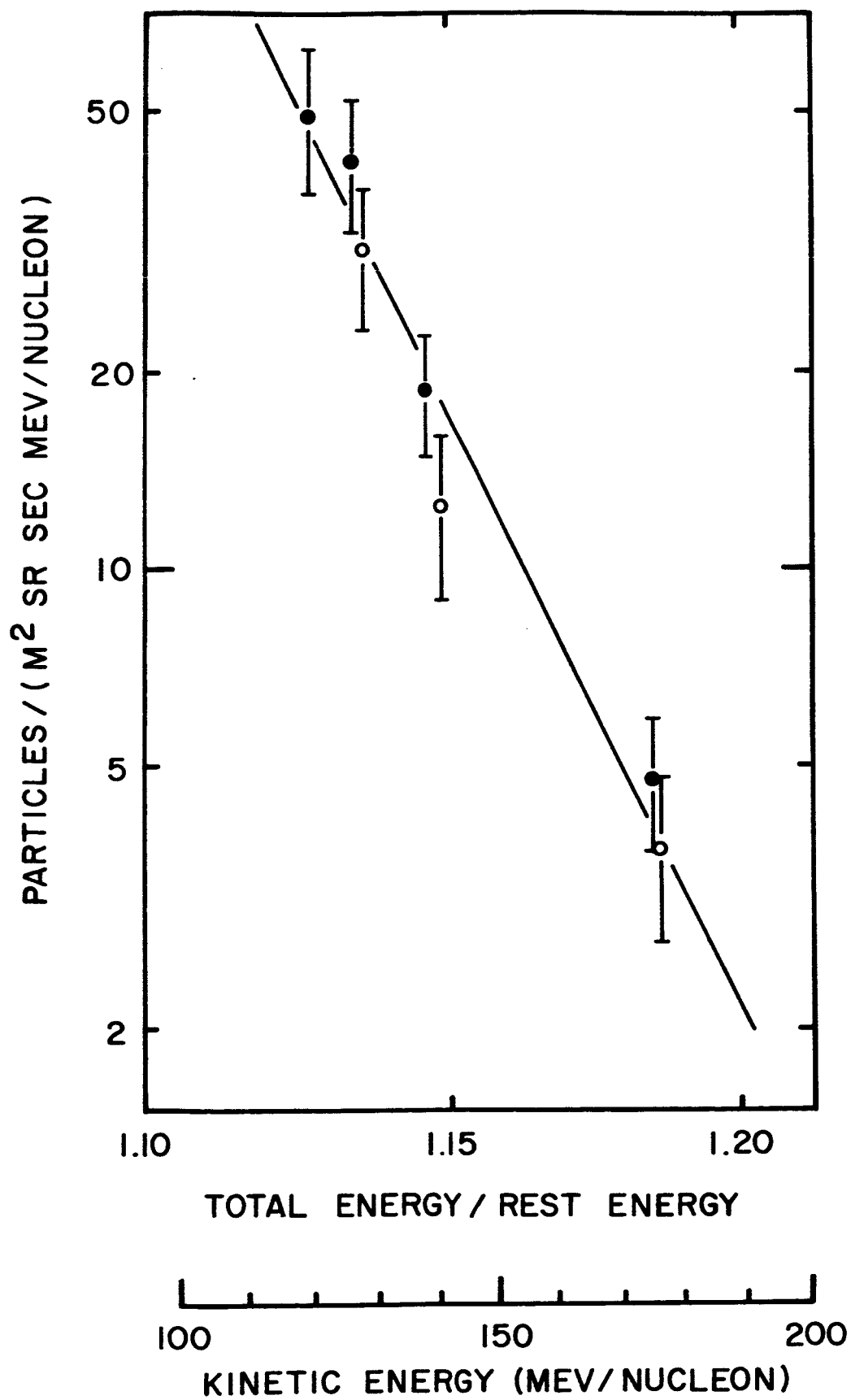


FIGURE 1

PROTON TO HELIUM NUCLEI RATIO

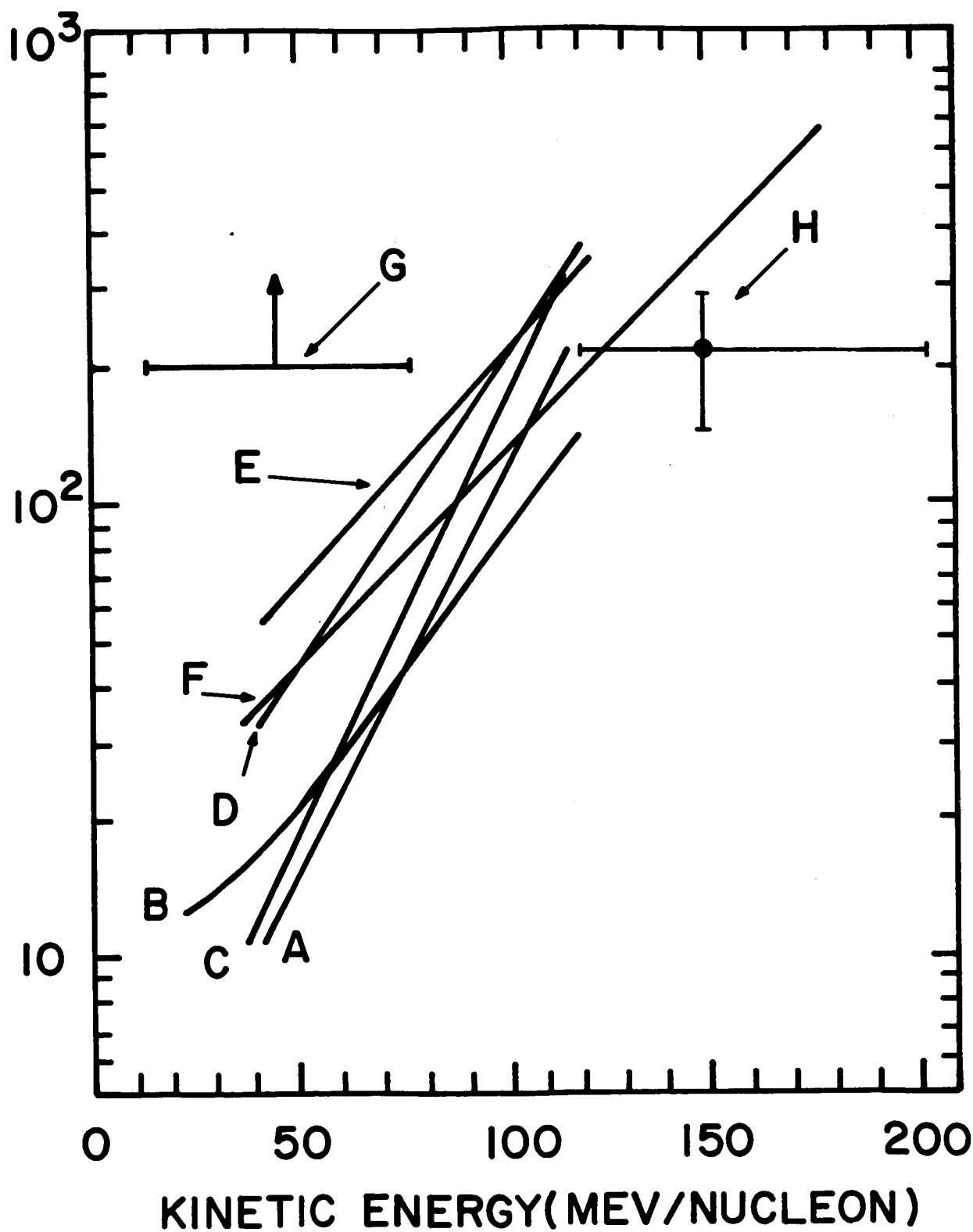


FIGURE 2